Evolution of light source technology to support immersion and EUV lithography

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ABSTRACT

Since the early 1980's, the resolution of optical projection lithography has improved dramatically primarily due to three factors: increases in projection lens numerical aperture, reduction of the imaging source wavelength, and continued reduction of the *k1* factor. These three factors have been enabled by the concurrent improvements in lens making technology, DUV light sources, photoresist technology, and resolution enhancement techniques. The DUV light source, excimer KrF and ArF lasers, has entered main stream production and now images more than 50% of the critical layers in today's leading edge devices. Looking forward to both immersion lithography and beyond to EUV lithography, new light source technologies must be created to enable the continued progression of shrinking feature sizes embodied by Moore's law.

Keywords: Lithography light source, DUV, EUV, lithography, immersion lithography, MOPA

30 YEARS OF OPTICAL LITHOGRAPHY: FROM 1980 TO 2010

In the 1970's, most semiconductor manufacturers used contact or proximity printing to transfer the features on the mask to the wafer. Due to the effects of diffraction, proximity printing could not extend the resolution much below 3 μm. The resolution of contact printing is theoretically much better than proximity printing, but the mask acted as a source of defects and resulted in yield losses on the wafer. Hence projection lithography, for which the resolution is given by $k_1\lambda/NA$, gradually became a preferred means of lithographic imaging in semiconductor manufacturing. Optical Lithography emerged as the preferred lithographic technology for semiconductor manufacturing after many attempts at alternative technologies. The road traveled by Moore's Law is littered with these alternate forms of lithographic technology such as x-ray lithography and electron-beam lithography, vying to be the chosen mass-production technique. Advancements in optical lithography have outpaced all other technical approaches and allowed unprecedented success in the continued size and cost reduction of semiconductor devices. As optical lithography has continued to improve beyond all expert opinions, alternative lithographic technologies have been discarded. Interestingly, for the last 30 years, the demise of optical lithography has been consistently predicted to be about 8 years in the future, as illustrated in Figure 1.

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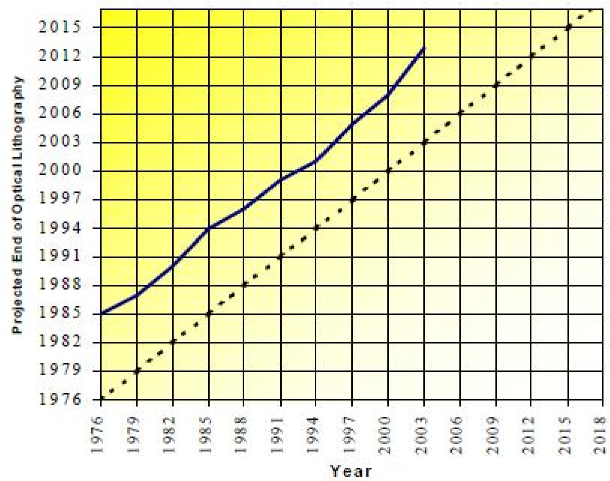

Figure 1 The demise of optical lithography? (from John Sturtevant)

Two key factors in the success of optical lithography are the continuous progress in projection lens-making technology coupled with the progression to shorter wavelength ultraviolet light sources. These factors have allowed the production of more complex and higher resolution steppers and scanners. For mainstream production, wavelength reduction of the exposing light source has progressed from Hg g-line (436 nm) to i-line (365 nm), to KrF (248 nm), and finally to ArF (193 nm) excimer radiation at present. In the future, EUV (13.5 nm) light sources are expected to succeed ArF. Figure 2 shows this progression of light source technology over time and the corresponding improvements in imaging resolution that have been achieved.

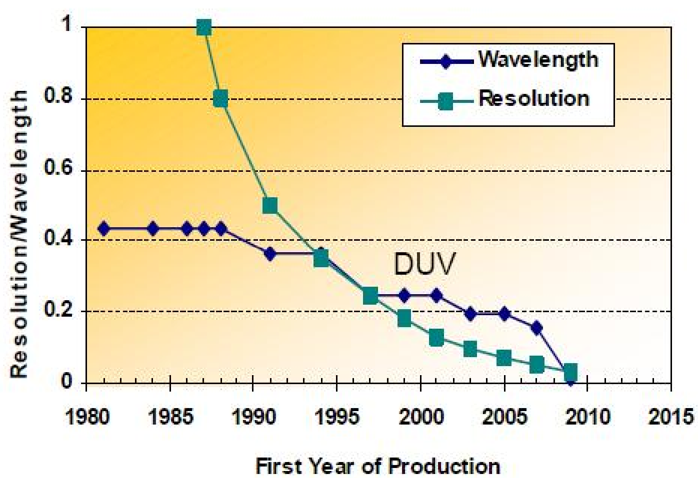

Figure 2 Trends in imaging resolution and exposure wavelength

Evolutionary improvements in lens design, optical materials and coatings, polishing, metrology, and the perfection of the excimer laser as a stable DUV light source have allowed the construction of some of the most complex, precise, and productive optical systems in any field. Advancements in

the last 5 years in aspheric lens manufacturing have allowed the construction of higher numerical aperture forms (>0.7 NA) pushing the limits of optical lens technology. Improvements in fused silica lens material for 248 nm DUV scanners and later calcium fluoride to resist the damage of the more energetic photons produced at 193 nm have allowed this continued progression of lens technology. Table 1 highlights the 30 years of lens making progress leading to incredible improvements in imaging resolution.

Table 1 30 years of lens evolution with corresponding imaging wavelength (data courtesy of Carl Zeiss)

Wavelength	436 nm	365 nm	248 nm	193 nm
NA	**0.28**	**0.40**	**0.57**	**0.85**
Resolution (nm)	1400	700	250	80
k_1-factor	**0.90**	**0.77**	**0.57**	**0.35**
1st prototype	1975	1987	1995	2003

LITHOGRAPHY LIGHT SOURCES

The Semiconductor Industry Association (SIA) roadmap identifies that light sources at four wavelengths, krypton fluoride (KrF), argon fluoride (ArF), fluorine (F_2) and Extreme Ultraviolet (EUV), are required to enable the industry to meet resolution roadmap well into the next decade. In today's fabs, deep ultraviolet (DUV) lithography tools in production use both KrF and ArF light sources. KrF light sources image patterns of 250 nm to just below 100 nm. Tools using ArF light sources are now being used for imaging patterns of at the 90 nm node and below. The lithography community currently expects to be able to extend ArF scanners to 45 nm production, and possibly to the 32 nm node, with liquid immersion lenses.

Resolution and throughput have been the primary drivers for the development of narrower spectral line widths and higher output power in each new generation of light source. Spectral power, the ratio of optical output power to the spectral line width, is a convenient metric to track the advancement of the light source capability. In Figure 3, the spectral power of KrF light sources is shown to have increased by more than 10x from 1990 to 2004. The progress of ArF light sources, leveraged heavily by the advancements in KrF, has achieved more than 50x improvement in spectral power in a much shorter time period. A second factor has played a tremendous role in the success of ArF; the recent successful application of master oscillator power amplifier laser technology (MOPA) to lithography light sources.[1]

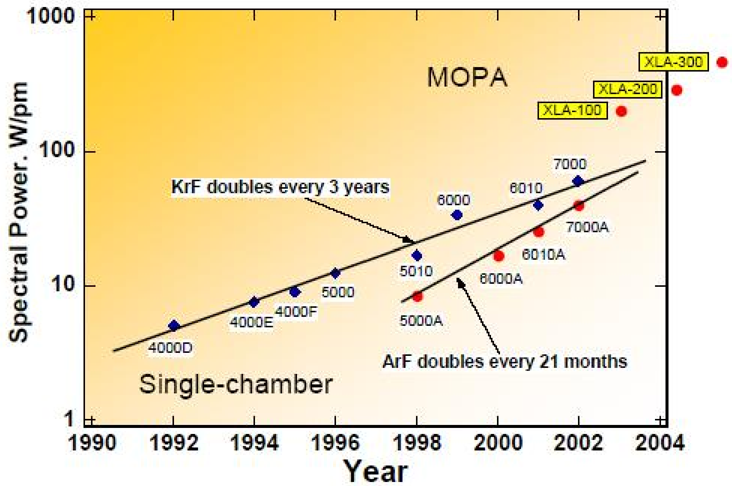

Figure 3 Trends in Spectral Power for Cymer's lithography light sources

MOPA

Historically, the majority of the approximately 2500[2] DUV lithography light sources installed today have used a single resonator design, in which one discharge chamber is responsible for not only generating a narrow emission spectrum, but also producing high power with precisely controlled pulse energy. The chamber operates together with optical components within the light source to produce narrow spectral bandwidths by selecting a small portion of the full spectrum generated by the chamber, and discarding the remaining out-of-band light energy. Since the line-narrowing process results in a reduction in light energy, a single chamber design must increase its discharge repetition rate in order to meet higher output power requirements. This limitation forces the light source designer to consider a system optimization tradeoff between spectral bandwidth and pulse energy.

In 2003, Cymer pioneered the application of a dual-chamber, MOPA architecture to ArF lithography light sources. This development overcomes the performance limitations of a single-chamber design. In the MOPA configuration, the functions of spectral bandwidth and pulse-energy generation are separated between two chambers, with each chamber independently optimized for one performance parameter. This approach enables the simultaneous improvement of both spectral bandwidth performance and increased output power without necessarily increasing repetition rate.

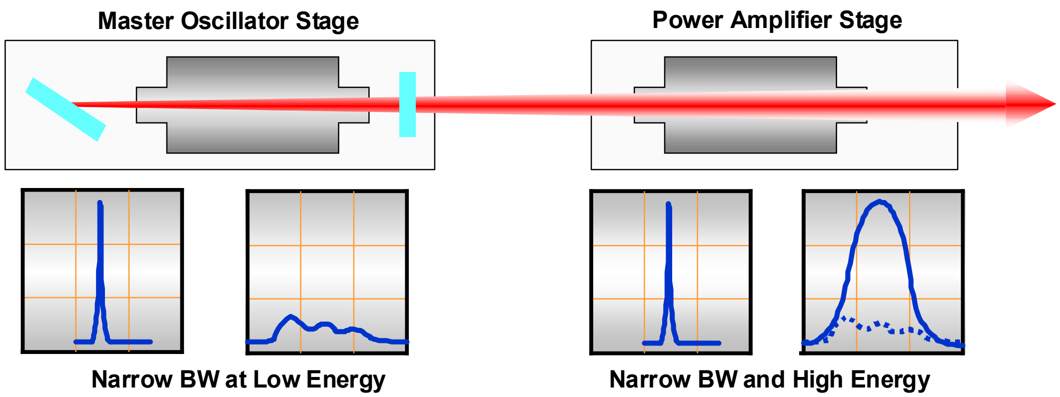

Figure 4 The MOPA architecture separates the spectral bandwidth and pulse energy generation functions into two separate chambers

As shown in Figure 4, the first discharge chamber, the master oscillator (MO), is designed to produce output with a very narrow spectrum (typically ≤ 0.2pm FWHM) at very low-pulse energy (typically 1mJ) when excited by compressed, short-duration, high-voltage electrical pulses. The MO chamber is situated within a resonator structure, consisting of an output coupler and a high-dispersion line-narrowing module (LNM). The second chamber is the power amplifier (PA). The PA discharge amplifies the line-narrowed, low-energy output pulses from the MO to a higher energy level to meet output power requirements (typically 40-80W), with no change to the spectral properties of the light. Synchronization between MO and PA chamber discharges is essential to the amplification process. The PA discharge must begin at the correct point of the MO pulse to ensure that spectral bandwidth properties are maintained.

The MOPA technological breakthrough also allows chipmakers to operate excimer light sources at greater than 2x the pulse energy compared to the previous generation of single-chamber excimer light sources. High-pulse energy operation at the light source output results in a higher nominal energy per pulse at the wafer, which in turn, results in a net 30%-50% reduction in pulses fired for each exposure and lower cost of operation.

CHALLENGES OF IMMERSION

There has recently been a great deal of interest in ArF immersion lithography to follow the current implementation of "dry" ArF lithography. The use of a suitable liquid between the projection lens and the wafer, such as water in the case of 193nm lithography, can provide one of two benefits. For current lens numerical apertures, immersion reduces the incident angle of light into the resist, which leads to improved Depth of Focus. Alternatively, these smaller angles can also allow the extension of lens designs to higher numerical apertures (effective NA > 1), which provides higher resolution.[3] Figure 5 shows the historical trend of lens numerical aperture along with estimates for future immersion lens NA.

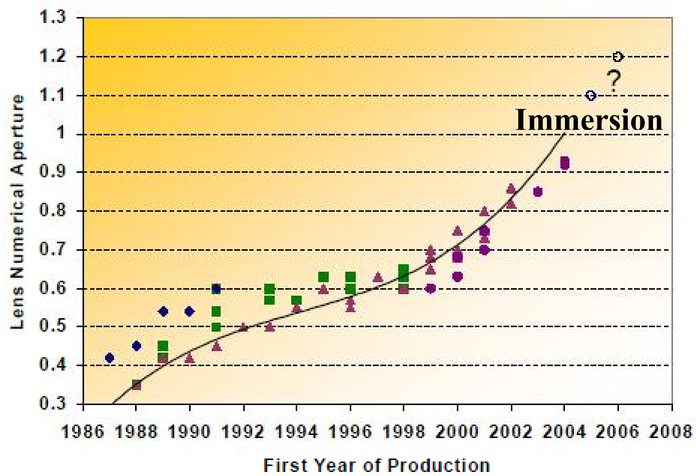

Figure 5 Historical trends in lens numerical aperture (NA)

For the use of immersion with existing lens designs, the implications for the light source are minimal, since the source has already been designed to meet the imaging requirements of the lens. However, for new higher numerical aperture designs, there is a continued demand for smaller bandwidth as we have seen in the past. But at very high numerical aperture, it is likely that dioptric lenses will become physically too large for practical manufacturing and catadioptric design forms will begin to be used. This may offer some relief for light source bandwidth, but will depend on the design details of the lens and the trade-offs with other key manufacturing and materials tolerances.

Another likely trend at very high numerical aperture is the need to use polarized light illumination for increased image contrast. The use of TE polarized light provides higher contrast than mixed or TM polarized illumination. The efficiency and other design characteristics of the polarized light illuminator will determine possible new light source requirements such as higher power or improved polarization stability.

Since immersion lithography will be used for higher resolution process nodes, the light source will also need to contribute to shrinking process margins with continued improvements to performance characteristics such as pulse energy stability and wavelength and bandwidth stability. Active feedback and control of such parameters is likely to be needed for both enhanced control and matching between systems.

Table 2 gives the critical dimension roadmap to the end of this decade. Moving forward, the adoption of 193 nm immersion lithography will require ArF light sources to support a much greater percentage of the leading-edge imaged layers through the end of the decade. At the end of the decade, these will be replaced by extreme-ultraviolet (EUV) light sources, at the leading edge. There will be further reductions in k_1, bringing in with it advanced resolution enhancement techniques such as double exposures, custom illuminations, polarization control, etc.

Table 2 Critical Dimension Roadmap

1st Year HV Manufacturing	2004	2006	2008	2010
Technology "Node"	90 nm	65 nm	45 nm	32 nm
Min. ½ Pitch (Logic/DRAM/Flash)	120 – 100 nm	100 – 80 nm	80 – 65 nm	55 – 45 nm
Lithography Technology	λ=193 nm NA=0.75 – 0.85	λ=193 nm NA=0.85 – 0.93	λ=193 nm NA=0.92 – 1.25	λ=193 nm NA>1.3 λ=13.4 nm NA=0.25
Enabling Light Source	Cymer MOPA XLA 100	Cymer MOPA XLA 105	Cymer MOPA XLA 200/300	Cymer MOPA Cymer EUV

EUV LIGHT SOURCES

EUV light sources present an entirely new challenge to the lithography community. Many papers have described the industry and market drivers. Programs are underway at various companies and consortia around the world pursuing different source concepts to meet the basic performance requirements of an EUV source for production introduction at the end of the decade. Basically, there are two basic approaches being considered for EUV lithography sources; laser produced plasma (LPP) and discharge produced plasma (DPP) and have been described elsewhere.[4] The three principle parameters concerning the feasibility of EUV lithography have been power, debris, and lifetime. The requirements for the output power of the source has jumped at almost every industry meeting and is directly related with the throughput requirements of the scanner. It has been modeled that to reach 100 wafers per hour, more than 115W of EUV power is required at the input to the scanner. Figure 6 shows the dramatic increase in EUV power requirements over the last several years.

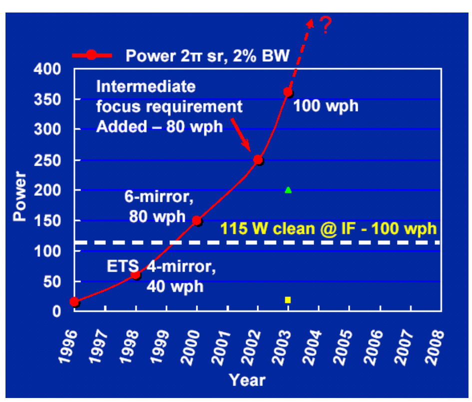

Figure 6 EUV source power trends

All of the source concepts involve the generation of plasma operating within a vacuum environment. Debris generation due to the plasma interaction with elements in the chamber or the

source material itself will create rapid contamination of any plasma facing optics and is considered one of the most critical challenges for this technology.

After many years of investigating a dense plasma focus DPP light source[5], Cymer initiated an investigation into LPP sources.[6] The findings of this study were recently published and can be summarized as follows.[7] The production output power requirements of > 115 watts drives the technology selection process. Only an LPP light source concept can possibly meet the power demands to make EUV lithography feasible. To drive this concept, several excimer lasers, similar to those used for DUV lithography can be used to excite the source material and produce suuficient energy to drive the exposure tool. Figure 7 illustrates this LPP source system concept.

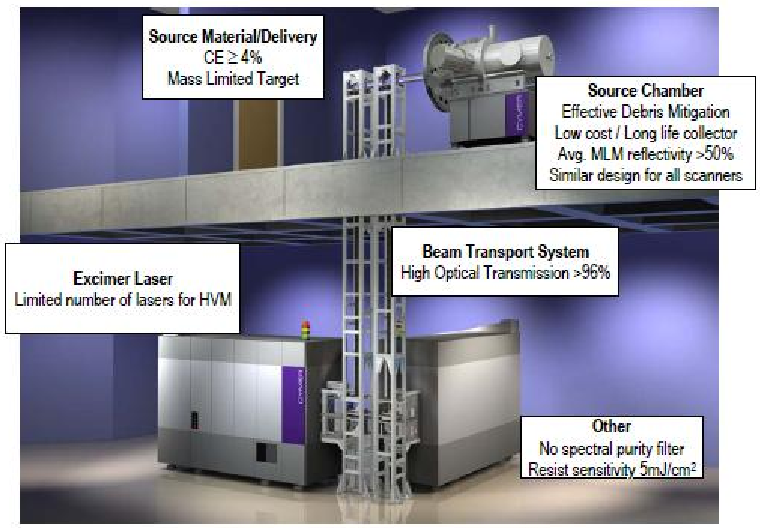

Figure 7 LPP EUV Source System Concept

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